OPERATING SPECIFICATIONS FOR A ROD ANODE, LOW INDUCTANCE, HIGH POWER MITL*

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ABSTRACT

A new magnetically insulated transmission line (MITL) has been successfully tested on the PITHON generator at peak currents up to 3 MA with the FWHM of 160 ns. This low inductance MITL (water line to load = 19 nH) features an anode which is constructed of 120 stainless steel rods 6.3 mm in diameter and 27 cm long (20 cm < r < 47 cm). The advantages of this rod anode are that it provides a high conductance pumping path of the anode-to-cathode (A-K) gap, it is simple to repair, and it provides access for erosion switch plasma injection. The inductance penalty of the rods was found to be negligible. The current lost along the MITL, with an imploding plasma as the load, was measured for several test conditions including 8 mm and 6 mm constant A-K gap spacings, use of erosion switches, early time asymmetric current, and enhanced prepulse. An array of Faraday collectors was used to determine the radial position of the current losses. The percentage of current lost was 2% at peak current and 7% at the implosion time for the optimum operating conditions.

1. INTRODUCTION

The propagation of multiterawatt electromagnetic pulses in a low inductance vacuum transmission line requires magnetic insulation of the electrons. These magnetically insulated transmission lines (MITLs) are used to transport the electromagnetic energy from large diameter water lines (1-2 meters) to the diameter of the load region (2 to 10 cm). MITLs have usually been constructed with continuous conductors as the electrodes. The anode of the MITL discussed in this paper has been partially constructed of stainless steel rods. There are four major advantages to the rod anode: it provides a high conductance pumping path of the A-K, it is simple to repair, it provides convenient access for erosion switch plasma injection, and it suppresses azimuthal current flow, thus the inhibiting formation of destructive arcs.

The new MITL discussed in this paper was designed to drive an imploding plasma load. This MITL will be used as the lower half of the Double-EAGLE (Reference 1) triplate vacuum feed when the generator becomes operational later this year. This MITL has been tested on the PITHON generator with the test conditions chosen to simulate the expected conditions of Double-EAGLE.

The current losses along the MITL with an imploding plasma as the load were studied for several test conditions. The test conditions include: (1) a reduced A-K spacing from the baseline value, (2) early asymmetric radial current flow to simulate the effect of an asymmetric injected wave on the power flow, (3) erosion switch plasma injected into the rod anode region to sharpen the current pulse shape, and (4) enhanced prepulse. The current loss along the MITL was measured by subtracting the current delivered to the load from the current injected into the MITL. The results of the current loss measurements for the baseline conditions (8.0 mm minimum A-K spacing, symmetric radial current, no erosion switch plasma, and minimum prepulse) are as follows: (1) less than 1.0% current loss prior to the time of peak current, (2) 2.0% loss at time of peak current, (3) losses increasing to 7.0% at the time of implosion (peak in the X-ray output signal). The largest current loss observed in this series of experiments (10.0% at peak current and 15% at the time of implosion) was measured for the case of a reduced A-K spacing of 6 mm.

The distribution of the current loss along the MITL was measured with Faraday collectors at three radial locations. The data from these collectors show that the electrons are magnetically insulated at the time of peak voltage, that the current losses prior to the time of implosion occur along the entire MITL, and that the losses prior to the time of implosion increase with the radiation output.

2. DESCRIPTION OF THE EXPERIMENT

A drawing of the MITL is shown in Figure 1. The minimum A-K gap was set at either 8 or 6 mm. The machine diagnostics were as follows: IØA--the average of three segmented Rogowski coils, which measured the current injected into the MITL; IPU--a Rogowski coil, which measured the load current; capacitive voltage monitors, which measured the voltage at the termination of the water line; and three unfiltered Faraday collectors mounted at three radial positions along the MITL. X-ray diagnostics were fielded on these experiments.

The plasma erosion switches are similar to those used for previous PITHON experiments (Reference 2). However, the plasma erosion switches

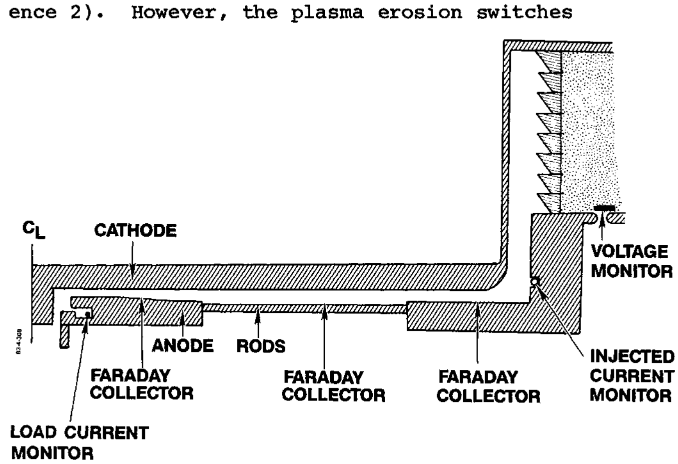

Figure 1. Side view drawing of the MITL as it was mounted on PITHON.

*Work supported by the Defense Nuclear Agency.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1983	**N/A**	**-**

4. TITLE AND SUBTITLE
Operating Specifications For A Rod Anode, Low Inductance, High Power MITL

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Physics International Company 2700 Merced Street San Leandro, CA 94577

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

were placed at a larger radius than the previous experiment. The use of the switches at a larger radius required a uniform plasma density over a greater area, thus the number of plasma injection guns was doubled from 6 to 12. The change in the plasma velocity due to doubling the number of guns was measured prior to the experiment to determine the correct plasma gun to machine timing.

Prepulse was introduced for certain test shots by shorting the prepulse slab at 14 locations.

3. EXPERIMENTAL RESULTS

A summary of the data obtained during this session is presented in Table 1. The percentage of current lost shown in columns 6 and 7 was computed from the current injected into the MITL (IØA) and the current delivered to the load (IPU). The number of millicoulombs of charge switched is computed by integrating the current loss until the switch opens. The implosion time is computed by subtracting the time of current zero from the time of maximum radiated power (peak in the X-ray diode waveform).

Table 1. Data summary.

Tests	Shot	Erosion Switch	Number of Millicoulomb Switch	Peak Current Injected (MA)	Current Loss At Peak Current (%)	Current Loss At Time Of Implosion (%)	Relative X-Ray Radiation Yield
I. Measure Inductance - Fixed Inductor Load							
rods	2743	no		3.47	0.0	-	-
no rods	2754	no		2.05	0.0	-	-
II. Baseline - Imploding Plasma Load, 8.0 mm A-K							
	2739	no		2.57	1.6	6.0	-
	2740	no		2.78	2.5	9.9	0.51
	2746	no		2.85	0.0	4.1	0.36
III. Reduced A-K Spacing - 6.0 mm A-K							
	2741	no		2.93	9.6	15.1	0.47
	2742	no		2.79	-	-	0.32
IV. Early Current Asymmetry							
	2750	yes - 1/2	11.6	2.92	3.1	5.2	0.51
	2752	yes - 1/2	33.7	2.87	6.3	12.8	0.34
	2753	yes - 1/2	47.5	2.53	7.5	6.7	0.15
	2751	yes - 1/2	60.00	3.11	51.5	40.0	-
V. Erosion Switches							
	2745	yes	11.3	2.90	5.2	15.6	-
	2744	yes	16.0	2.76	6.1	10.4	0.47
	2747	yes	21.1	2.96	0.3	9.0	0.47
	2749	yes	48.0	2.79	7.9	10.6	0.30
VI. Enhanced Prepulse							
	2755	no		2.37	5.9	7.7	0.36
	2756	no		2.51	13.6	15.8	0.43
	2758	no		2.45	5.3	6.7	0.62
	2760	no		3.10	6.5	8.0	1.00

Test I is a measurement of the total MITL and tube inductance with a rod anode (2743) and with a flat plate in place of the rods (2754). For these shots, the MITL was shorted at the gas puff nozzle [position (b), Figure 1]. The rods did not add any measurable inductance to the MITL.

The second test shown in Table 1 was at the baseline conditions. The results of Test II show current losses that are consistent with losses observed on other PITHON MITLs (Reference 3). The radiation yield value obtained on Shot 2740 is within experimental error of the value predicted. The measured voltage, current, and current loss on Shot 2740 are shown in Figure 2.

The third test was to reduce the A-K gap by 2 mm and confirm that 8 mm is the optimum gap. The results in Table 1 show that current losses doubled when the minimum A-K gap was closed from 8 to 6 mm.

SHOT 2740 (8 mm A-K, imploding plasma load, baseline conditions)

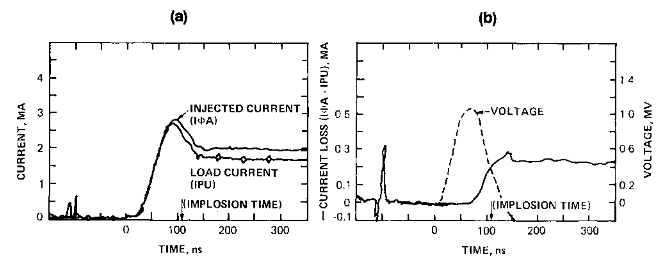

Figure 2. Shot 2740 at the baseline conditions. (a) Overlay of the injected current and the load current showing that current losses begin at peak current. (b) The loss current (injected current-load current) and the voltage as functions of time.

The fourth test was to produce early asymmetric radial current, thus simulating the expected Double-EAGLE early pulse shape. The current and voltage waveforms obtained when shorting the lower half of the MITL with the erosion switches are shown in Figure 3. Figure 3(a) is a diagram of the MITL. The shaded region indicates the approximate location of the initial plasma erosion switch injection. The voltage and current waveforms [3(b) and 3(c)] indicate that there is a large inductive load (high voltage, lower current) on the top of the MITL until the erosion switch opens on the bottom

SHOT 2752 (8 mm A-K, imploding plasma load, asymmetric wave)

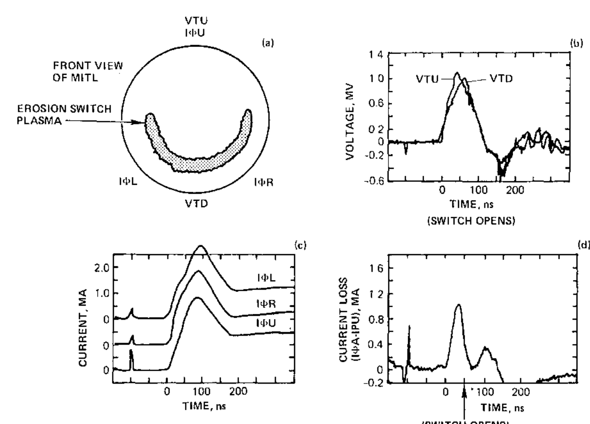

Figure 3. Shot 2752 asymmetric radial current test. (a) Front view diagram of the MITL. The shaded area is the region initially shorted by the erosion switch plasma. (b) The voltage waveshape. Note the lower (VTD) voltage prior to the switch opening indicates a shorted load. (c) Current waveforms showing the initial asymmetries in the radial current. The arrow indicates the time the switch opens. The current loss is shown in (d).

at t = 50 ns. The resulting current losses are presented in Figure 3(d). The peak in the current loss prior to 50 ns is due to the closed erosion prior to 50 ns is due to the closed erosion switch. The integral of this peak is the amount of charge that has been switched asymmetrically (34 mC). The results in Table 1, Test IV, indicate there is an increase in the current loss by a factor of 2 (Shot 2752) when switching 34 mC. Opening the minimum A-K spacing (2753) or switching only half the charge reduced the losses to the baseline level. This effect implies no increase in current loss for Double-EAGLE when the two modules switch within 10 ns. A self-sustained arc was produced when more than 60 mC was switched (Shot 2751). The arc on Shot 2751 was uniformly distributed over half the MITL (only slight damage to the electrodes). In spite of the arc, half the current passed through the load, thus illustrating the ability of the rod anode to inductively isolate the arc from the rest of the MITL.

The fifth test was to determine the effects of erosion switches on a low inductance MITL. For this test, the plasma erosion switches were uniformly distributed at a large radius in the MITL. The data shown in Table 1, Test V (2745, 2744, 2747, 2749) indicate no dependence of the current loss on the amount of charge switched. However, when comparing the average current loss with switches to the baseline case, there is a factor of 2 increase in the percentage current loss.

The sixth test was to measure the effects of prepulse on current loss and radiation yield. A sample of the voltage and current obtained with the enhanced prepulse is shown in Figure 4. The current losses are about double the baseline values. The radiation yield with prepulse is within experimental error of the expected PITHON radiation output at this current level.

SHOT 2760 (8 mm A-K, imploding plasma load, with prepulse)

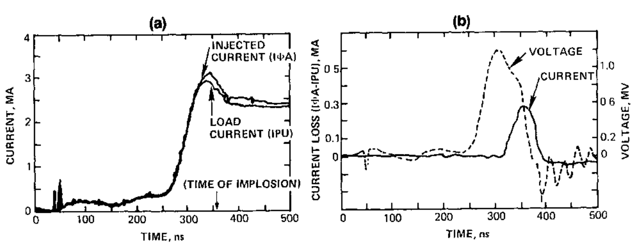

Figure 4. Shot 2760 with enhanced prepulse. The injected and load currents are shown in (a). The current loss and voltage are shown in (b). The presence of enhanced prepulse doubles the current loss when compared to the baseline case.

The results of the Faraday collector measurements are shown in Figure 5. The loss current density (A/cm^2) data from each of the three collectors has been multiplied by the appropriate area of the MITL to obtain the current loss in each of the three regions shown. The total current loss (IØA-IPU) is obtained by summing the current loss of all three regions. The current loss in each region is plotted at four times during the machine pulse; 37 ns (peak voltage), 80 ns (peak current), 90 ns (15 ns before time of

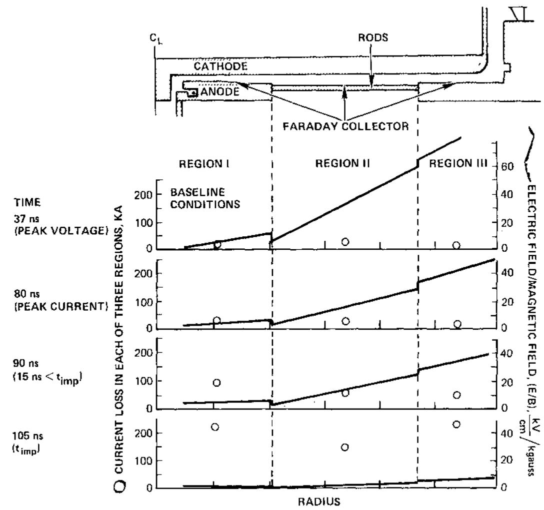

Figure 5. The current loss in each of three regions of the MITL as determined from the Faraday collector data. This current loss is plotted with E/B as a function of radius at four times during the pulse: time of peak voltage (37 ns), time of peak current (80 ns), 15 ns before the time of implosion (90 ns), and at the time of implosion (105 ns). These data show the current losses occur along the entire MITL and increase from 80 ns until the time of implosion, even though E/B is decreasing, thus suggesting the losses increase with the radiation output.

implosion), and 105 ns (time of implosion). Also plotted with the loss current is E/B as a function of position along the MITL.

Figure 5 shows that at 37 ns (time of maximum E/B for r > 9 cm) the criterion for magnetic insulation is satisfied since the current loss along the MITL is small. The current loss increases significantly after 80 ns but E/B is decreasing, which suggests the magnetic trapping should be better than at 37 ns. This increasing current loss could be due to A-K gap closure and/or negative ion formation (References 4, 5). There are two interesting observations to be made from these results. First the current losses occur along the entire MITL but increase more rapidly near the load. The second observation is that the current losses seem to scale with the radiation output since from 80 ns to the time of implosion the voltage and current are decreasing while the radiation output is increasing. The dependence of the current loss on a radiation output may be due to: (1) accelerated closure of the A-K spacing caused by ionization of the background gas or enhanced surface plasma heating and/or (2) increase in the production rate of negative ions in the surface plasma.

4. CONCLUSIONS

The Double-EAGLE lower MITL was tested on PITHON for operating conditions expected for the new machine. The new MITL had an anode partially constructed on rods. No inductance penalty was observed due to the rods. A summary of the current loss results is shown in Table 2. A minimum A-K spacing of 8.0 mm was found to be the optimum operating point of the MITL.

The results of Faraday collector measurements are that significant current losses begin after the time of peak current, that these losses occur along the entire MITL, and that the losses appear to be increasing with the radiation output.

Table 2. Summary of the current loss results.

	Test	Test Conditions	Current Loss At Peak Current (%)	Current Loss At Time of Implosion (%)
I.	Measure Inductance	• fixed inductor load • minimum A-K = 8.0 mm	0	-
II.	Baseline	• imploding plasma load • minimum A-K = 8.0 mm • symmetric radial current • no erosion switches • minimum prepulse	2.0	7.0
III.	Reduced A-K Spacing	• minimum A-K = 6.0 mm • baseline	10.0	15
IV.	Early Current	• asymmetric radial current • half erosion switches • baseline	5.0	8.0
V.	Erosion Switches	• with symmetrical positioned erosion switches • baseline	5.0	11.0
VI.	Enhanced Prepulse	• prepulse • baseline	8.0	10.0

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